# Equilibrium Degradation Levels in Irradiated Erbium-Doped Fiber Amplifiers

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**Abstract (35 words)** – We show that local EDFA degradation can be tuned reversibly across equilibrium levels determined by local pump power and dose rate, while the dose is cumulated. This remarkable property inspires a physical, validated degradation model.

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## I. INTRODUCTION

Erbium-doped fiber amplifiers (EDFA) could be used in high-output power fiber laser sources operating in space, as those required in optical inter-satellite links (OISL) or remote sensing (embedded LIDAR). They have been flying around the Earth already, in satellite fiber optic gyroscopes (FOG). Mechanisms of the radiation-induced degradation of EDFA remain nevertheless unclear despite the significant amount of studies that have been published for more than 20 years [1]. Degradation consists in "darkening", an excess optical loss resulting from the formation of color centers upon ionization effects. It is characterized by the so-called radiation-induced attenuation (RIA), most often at pump or signal wavelengths. Unfortunately, guided radiations do not act as probes only. It is well known, notably, that light at pump wavelength (typically 980 nm) can mitigates the RIA. This effect being most probably due to photo-bleaching (PB), its efficiency depends on pump power. Pump-induced PB and its interplay with darkening have therefore to be properly characterized and understood to elucidate basic mechanisms and design physical explanatory/predictive models. To date, published works have generally not paid in the pump effect the attention it deserves: the pump power is not always specified (see, e.g. [2,3]), not taken into account in the interpretation [3], and EDFA lengths have been taken in the 1-3 m range [2]. These lengths are chosen to comply with operation conditions, but they result in an inhomogeneous distribution of pump power along the fiber (Fig. 1) and do not offer convenient conditions to elucidate basic mechanisms. In what follows, we use short fiber pieces to demonstrate new remarkable features revealing mechanisms that are included in a physical degradation model.

## II. EXPERIMENTAL

The measurement set-up is similar to that used in [4], except that the probe at 633 nm is not used. The fiber under test (FUT) is in-core pumped at 976 nm (temperature and fiber-Bragg grating stabilized laser diode) while being homogeneously irradiated in the beam of an X-ray generator (Inel XRG 3500, copper anode, 45 kV accelerating voltage). Dose rates given to the FUT are monitored by an ionization chamber (PTW 23342, UnidosE), placed right below the FUT. Two InGaAs photodiodes served as power-meters to estimate launched and transmitted pump powers as well as RIA:

$$\mathrm{RIA}_{980\ \mathrm{nm}}(t) = -\frac{10}{L \times \ln(10)} \ln\left(\frac{P_{\mathrm{out}}(t)}{P_{\mathrm{in}}(t)} \times \frac{P_{\mathrm{in}}(0)}{P_{\mathrm{out}}(0)}\right) \text{ in dB/m.}$$

$L$ = 2 cm is the FUT length, $P_{\mathrm{in}}(t)$ and $P_{\mathrm{out}}(t)$ are input and output powers at time $t$, respectively. $P_{\mathrm{in}}$ is constant ($P_{\mathrm{in}}(t) = P_{\mathrm{in}}(0)$) within a 1% fluctuation.

Samples consisted of various COTS and tailor-made erbium-doped fibers fabricated and drawn in our laboratory by the standard MCVD and solution doping techniques. This summary particularly reports on the Er80-4/125 fiber commercialized by Liekki (n-light) as a very highly doped erbium fiber designed for fiber lasers and amplifiers. We used very short fiber pieces to avoid amplification of the spontaneous emission (ASE) and ensure a uniform distribution of both pump power and excitation ratio of $Er^{3+}$ ions before irradiation. The pump power was always virtually constant across our 2 cm-long samples (varying by less than 0.8%). Fig. 1 presents the calculated pre-irradiation pump and excitation ratio profiles that would exist in a 2 m-long Er80 fiber pumped at $P_{\mathrm{in}}$ = 100 mW. In long fibers, ASE powers are not negligible and their profiles, together with those of pump power, excitation ratio, and PB efficiency, strongly depend on $L$ and $P_{\mathrm{in}}$. The subsequent introduction of a signal in the fiber will also change these distributions. By taking short fiber pieces, we free the problem from extrinsic spatial variations to retain a well-defined pump power as the only parameter. Profile variation effects, that additionally accompany changes in $P_{\mathrm{in}}$ or $L$ and are necessarily integrated when the RIA is averaged over several meters, are thus ruled out.

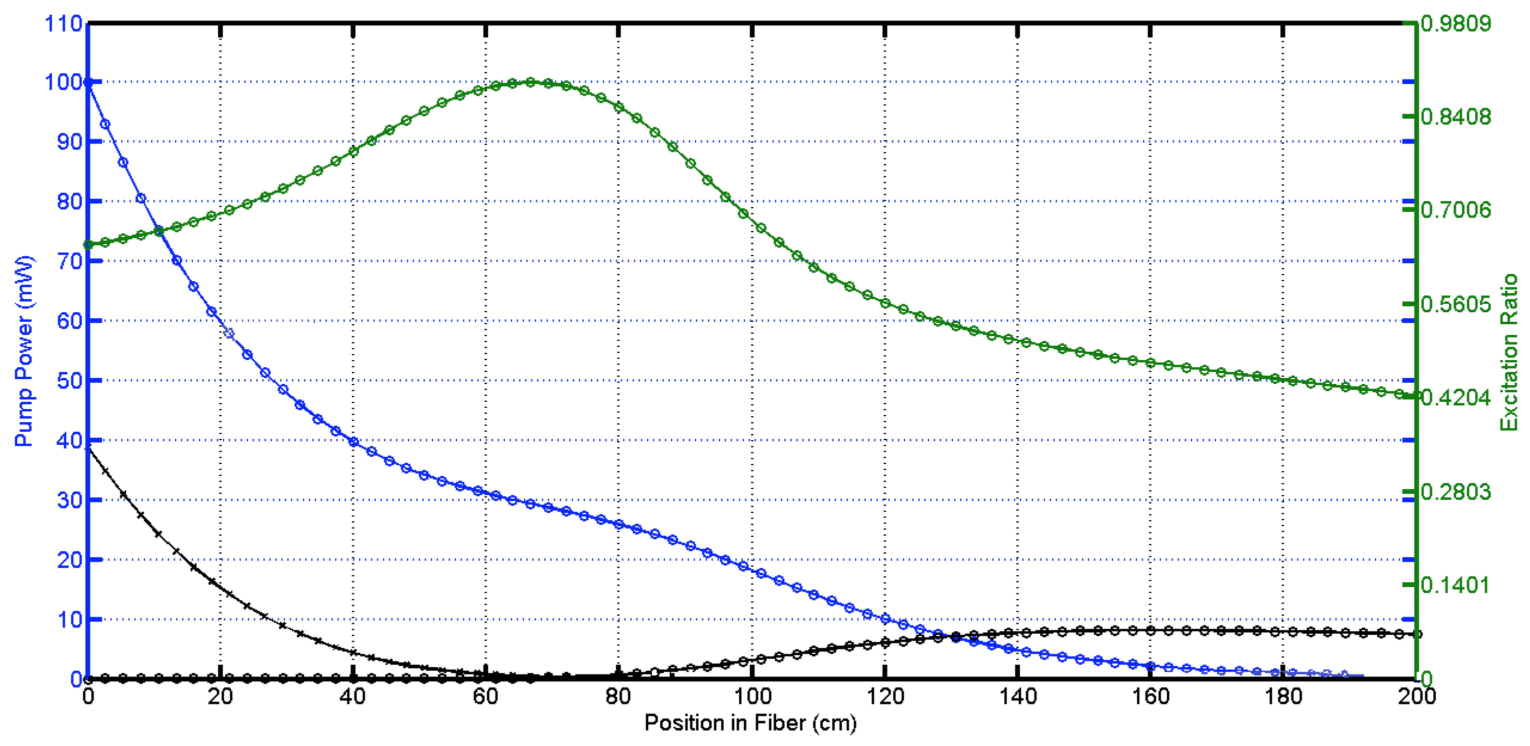


**Fig. 1.** Pump power (blue), co- and counter-propagative ASE powers (black) and the resulting excitation ratio (green) typical profiles in a 2 m-long Er80-4/125 fiber pumped at 980 nm with $P_{\mathrm{in}}$ = 100 mW (simulated with the *FiberLaserAmplifierToolbox* freeware).

## III. RESULTS

A typical experiment is reported in Fig. 2 for the Er80 fiber. A *unique* fiber sample has been irradiated and pumped continuously for almost 3 days. The dose rate $D'$ and the pump power $P_{\mathrm{in}}$ have been switched between various constant values, as indicated in graphs. The upper part of the figure displays the evolution of the RIA measured at 980 nm whereas the lower part gives the cumulated ionizing dose. The experiment can be divided into 3 parts: A, B and C. In A, the pump power was constant ($P_{\mathrm{in}}$ = 132 mW). The dose rate has been first set at 60 krad/min and then decreased by steps down to 40, 20, 11, 5, 2.6, 1.28 and 0 krad/min before being raised again to 5 and 11 krad/min. In the B region, the dose rate was constant ($D'$ = 11 krad/min) but $P_{in}$ was switched from 132 to 167.8 mW, 48.2 mW, and raised back to 132 mW. The pump power was again dropped to 48 mW to enter the C region where we started with $D'$ = 0 before switching to 20, 40, and 60 krad/min.

Each couple ($P_{in}$,$D'$) was maintained a sufficiently long period of time to observe the RIA can reach a steady-state level (hereafter termed equilibrium degradation level, EDL). EDL are found to increase with the dose rate and when pump power is decreased. This well reveals the competition between darkening and PB kinetics. After its initial steep increase, the RIA decreases in zone A despite the continuous increase of the dose! This uncommon fact would not be observed if the dose rate was switched before entering EDLs. EDLs are entirely determined by the couple ($P_{in}$,$D'$). They neither depend on the cumulated dose, i.e. the exposure history of the sample, nor on the starting darkening level. For instance, the couple (132 mW, 11 krad/min) is formed twice in A and once in B, at various total doses and different initial RIA levels, but it always results in the same EDL around 30 dB/m (dashed horizontal lines highlight EDLs obtained for identical pump/dose rate couples). In the absence of ionizing radiation ($D'$= 0), the RIA does not decrease down to zero: the pump does not permit full recovery of the transmittance, suggesting that part of color centers is not bleachable. EDLs($P_{in}$,0) appearing in Fig. 2 (in regions A and C) are lower at higher pump powers (about 13.1 and 18.5 dB/m at $P_{in}$ = 132 and 48.2 mW, respectively). The zero-dose rate case is actually a particular one because the EDL then depends on the initial darkening level. We examined for instance the case of pure photo-darkening, when the pump is turned on at 132 mW, without x rays, starting from a new pristine Er80 sample (no initial RIA). As expected for an Er-doped fiber, the photo-darkening equilibrium level was very low, at 0.87 dB/m, far below the 13.1 dB/m value obtained when the same pump power is applied at $D'$ = 0 starting from a 20 dB/m darkened state. EDLs extracted from Fig. 2 are plotted in Fig. 3 as a function of dose rate for $P_{in}$ = 132 mW (EDLs of zone A), and 48.2 mW (EDLs in zone B and C). Data are well fitted by a power law with almost the same exponent close to 0.17. EDLs extracted from Fig. 2, zone B, are plotted in Fig. 4 as a function of pump power for $D'$ = 11 krad/min. Their pump power dependence again obeys a power law, with a – 0.48 exponent. Further experiments are needed to determine whether this value is dose rate sensitive (final paper).

A power law dependence of the RIA on the dose rate is not – a priori – an original finding, since the RIA was empirically found to vary as $D'^{(1-f)}\, D^{f}$, where $D$ is the dose and $f$ an exponent (close to 0.8 in [5]). What is new here is the fact that we deal with EDLs that do not depend on the dose (RIA is frozen at the EDL, even under continuous irradiation at constant $P_{in}$ and $D'$). We have therefore EDL $\propto (D'^{0.17}/P_{in}^{0.48})$, but EDL $\propto D^{0}$ !

To highlight how the RIA probe light affects the RIA level, tests were made on new fiber pieces at various dose rates, "without pump". To measure the RIA, the pump was just turned on periodically for a few seconds. Results are shown in Fig. 5 (one data point per second). The black plot has been obtained at indicated dose rates by lighting the pump at 132 mW for 5 s every 15 minutes (pump ignition time ratio 0.56%), or every hour (0.14%).

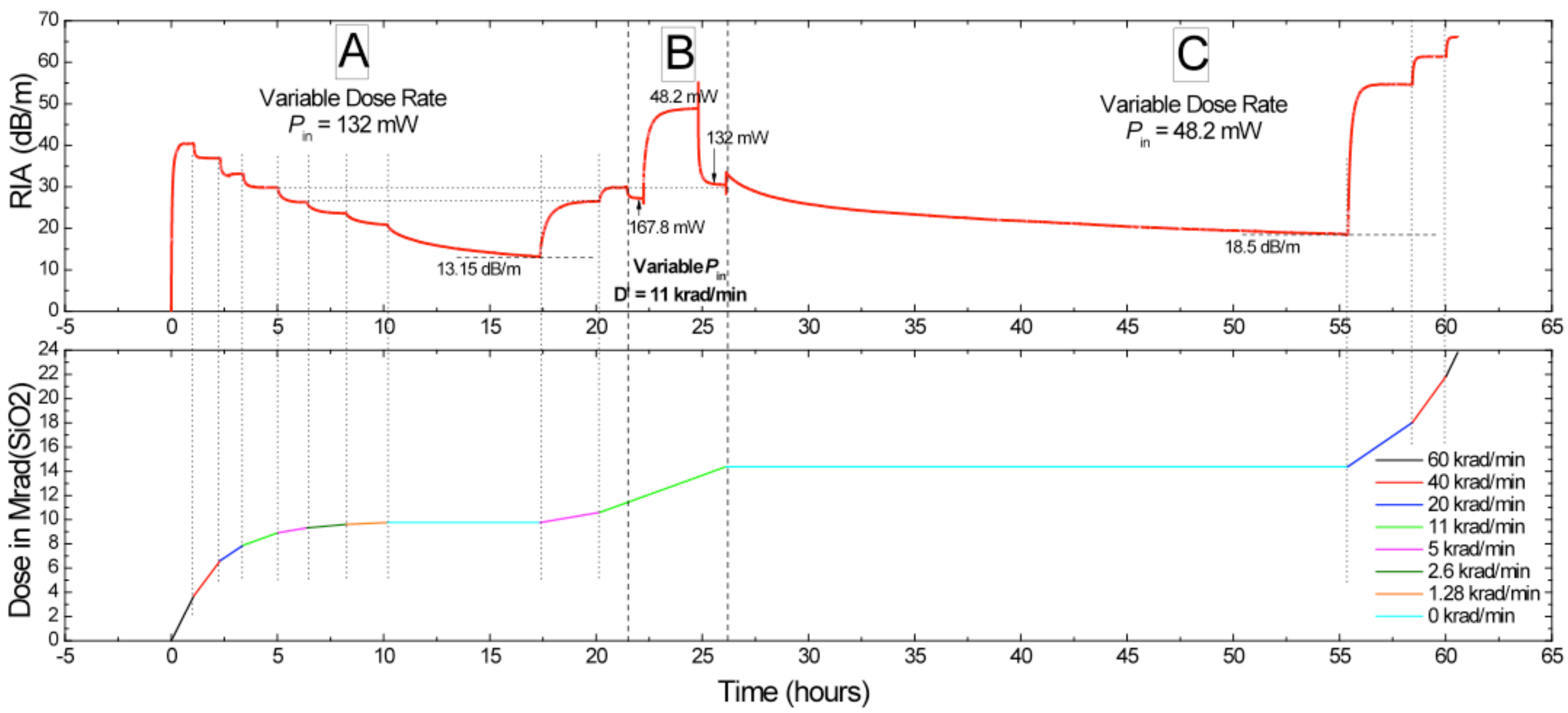


**Fig. 2.** Temporal evolution of the RIA under various pump power/dose rate couples (upper part), and the corresponding evolution of the cumulated dose in silica (lower part), applied continuously on the same 2 cm-long piece of the COTS Er80-4/125 fiber.

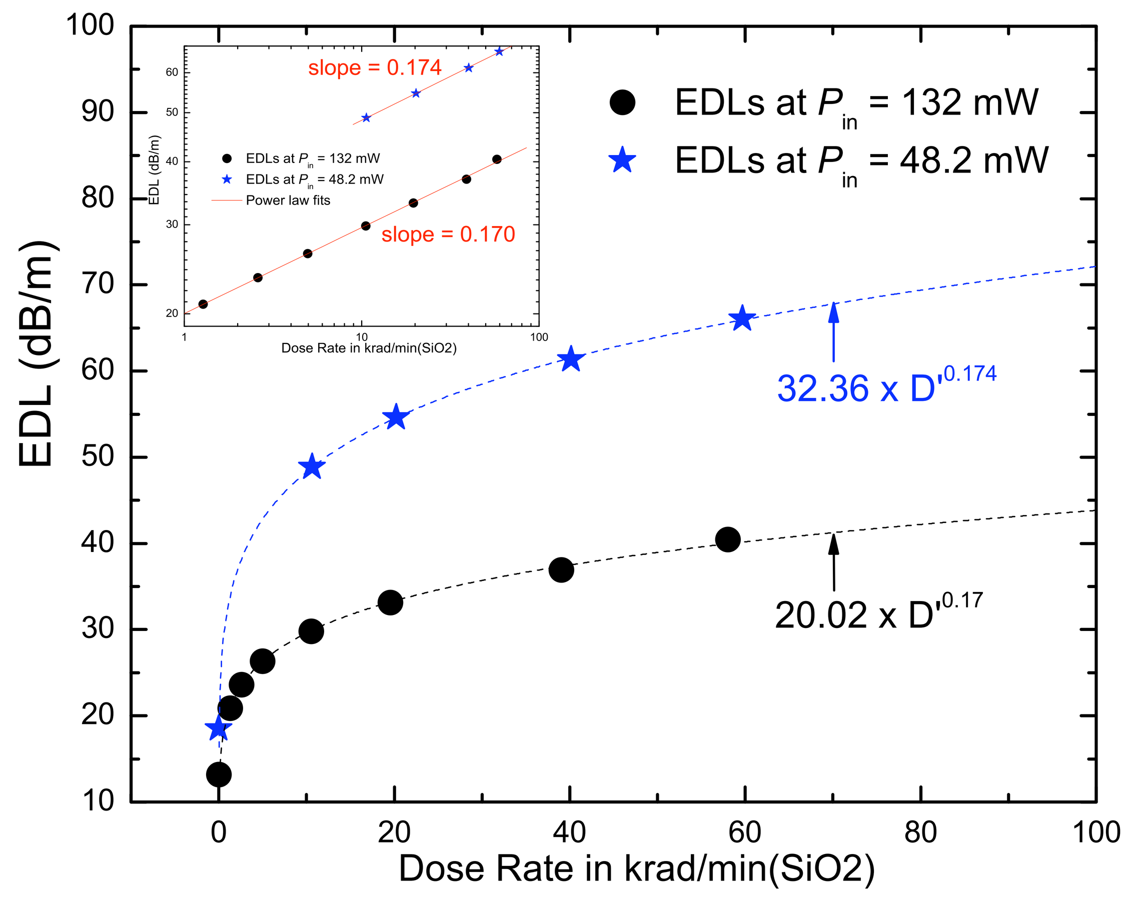


**Fig. 3.** EDLs as a function of dose rate for $P_{in}$ = 132 and 48.2 mW and power law fits. Inset: the same in log-log plots.

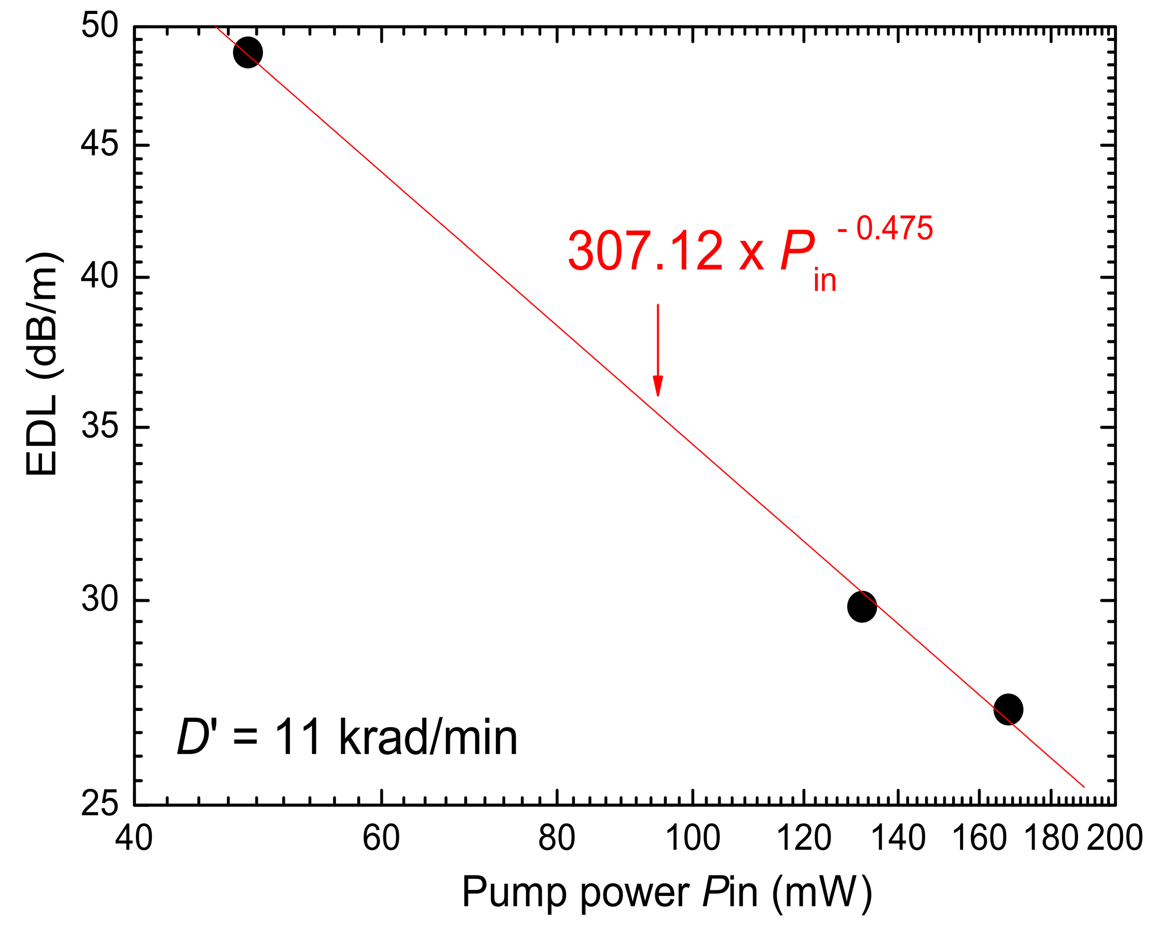


**Fig. 4.** EDLs as a function pump power for $D$' = 11 krad/min and power law fit to data.

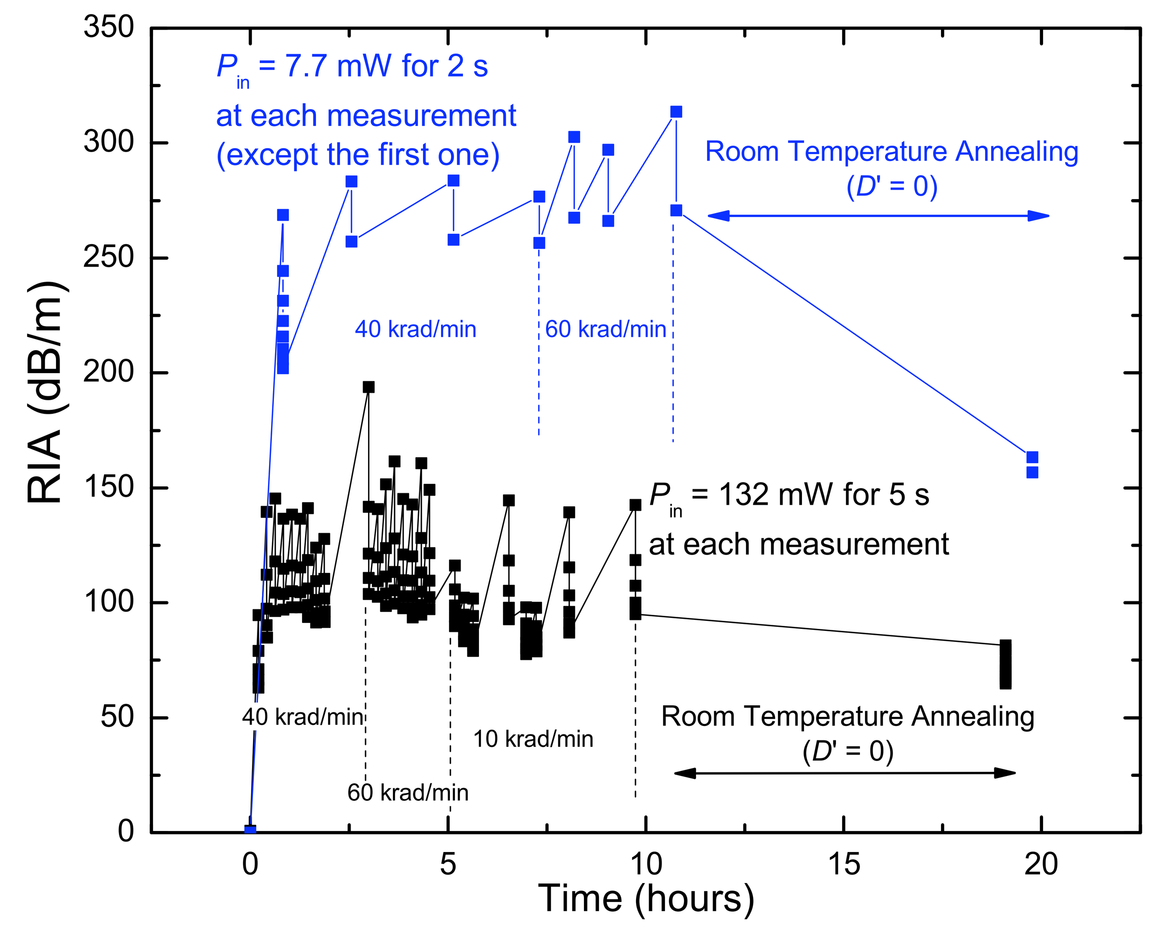


**Fig. 5.** RIA at 980 nm measured by short periodic pump ignition. Black: $P_{in}$ = 132 mW during 5 s each 15 min (and sometimes 1 h). Blue: $P_{in}$ = 7.7 mW during 2 s, pump ignition period = 1 or 2 h.

RIA levels are higher than those of Fig. 2, but the pump effect is still strong, preventing the RIA from a continuous increase and leading to its stabilization around 100 dB/m. To get the blue plot, the pump impact was reduced by dropping $P_{in}$ to 7.7 mW and the pump ignition time ratio to 0.06 and 0.03% (2 s ignition every 1 or 2 hours). Despite this reduction, PB is still sufficient to make the RIA stabilize, now around 260 dB/m. Even very short, low-frequency, low-power pump actions yield efficient mitigation. This reveals that measuring the 'intrinsic' RIA is a hard task! We finally estimated the room temperature annealing (RTA) by stopping x-rays and waiting for 9 h before the last RIA record. RTA is more significant when it starts from the higher RIA at 270 dB/m (blue data points, almost - 40 % in 9 h). The relative anneling is 4 times smaller when starting from 90 dB/m (black data points). In Fig. 2, RIA levels are such that RTA is rather weak. In presence of significant RTA, we could not reach almost perfectly the same EDL at 132 mW and 11 krad/min, as we did 3 times in 21 h.

## IV. Discussion And Modeling

Our investigation of the interplay between radiation induced darkening and pump-induced PB evidences remarkable properties. Under spatially homogeneous pumping, the RIA can be tuned reversibly by varying $P_{in}$ and/or $D$' while the dose is being accumulated. This could not be demonstrated using standard amplifier lengths. At fixed launched power and dose rate, regions of long fibers experiencing higher pump power (see e.g. Fig. 1) would reach their EDL rather rapidly, whereas RIA in low pump power regions would not stabilize readily. This kinetics difference would be reinforced with the passage of time, since lower pump power also means faster RIA build-up and higher pump losses… Therefore it will take much more time for the length-integrated RIA to reach a clear stationary level. This considerable delay makes very hard to observe "rapid" EDL switches on long fibers. Basically, EDLs provide a most relevant reference to assess the radiation-resistance of EDFA. They indeed set the maximum, i.e. the worst degradation level achievable at given ($P_{in}$,$D$'). Optimizing EDLs, rather than lower dose-dependent levels, focuses the discussion on 'rates' (pump energy rate and dose rate), while offering the best safety margin. For actual EDFA lengths, local EDLs increase as the fiber is exposed to irradiation, due to the development of pump absorption and power loss ($P_{in}$ decreases). Regions with initially higher (resp. lower) pump power will experience more (resp. less) efficient PB so their RIA, together with their local EDL, will increase slowly (resp. rapidly). In other words, lower EDLs are less rapidly damaged (raised). As regards the PB efficiency, the notion of high and low pump power is obviously related to the dose rate. A high power, i.e. yielding very efficient PB, refers to a power which is capable of photo-ionizing color centers at a frequency which is comparable to that of their formation (set by $D$'). For space-based applications, concerned with very low dose rates, "high pump powers" can be actually low. Not only the small $D$' will make initial EDLs low (2-3 dB/m at worst, at a point initially at 50 -100 mW and $2\times10^{-6}$ krad/min for Er80. Value extrapolated from fits of Fig. 3) but it will also ensure a very slow increase of this

EDL and of the RIA towards it. As a result, the 980 nm RIA of the Er80 fiber should not be significantly damaged in space. This conclusion is opposite to that of enhanced low dose rate sensitivity (ELDRS) found in [3], resulting in the prediction of higher degradation levels in space than in ground accelerated tests. Of course, our qualitative analysis must be refined and confirmed quantitatively by an accurate modeling.

We have been showing for a few years that physical models based on simple energy level scheme considering trapping, detrapping and recombination transitions, together with related set of coupled rate equations, represent a powerful tool to explain a variety of experimental behaviors in systems damaged by carrier ionization and trapping. We gave a global and validated modeling of dose rate effects inherent in such systems [6], and recently explained successfully on this basis [7] the interplay between pump and ionizing radiation in ytterbium-doped fibers previously demonstrated by our team [4]. For erbium-doped fibers, the physical model was built by inserting the minimal ingredients required to explain what we observed: electron-hole pair ionization, trapping (to form color centers) on 2 types of traps with different activation energies, photo-ionization of the shallowest trap (the second is optically disconnected to account for the non-bleachable part of the RIA), and recombination. The model cannot be presented in detail in this summary; it is of the same type as those introduced in [6,7]. In its present form, it is rigorously valid for fiber lengths tending to 0 (local model); longer fibers will be simulated after the implementation of this first module in a spatially-resolved self-consistent simulation code, eventually coupled with an EDFA simulator. Fig. 6 and 7 present a typical example of simulations aiming at reproducing the experimental protocole of Fig. 2. We show the simulation of the first 6 steps of zone A (Fig. 6) and of the sequence of zone B (plus beginning of C, Fig. 7). EDLs are correctly generated and well depend on the couples ($P_{in}$, $D'$) only. The power law dependence of the EDL on $D'$ and $P_{in}$ are qualitatively reproduced. The computed dose rate exponent (0.31) is almost twice the measured one, but this discrepancy most probably arises from the fact that simulation depicts too short fibers. The overall qualitative agreement with data, which is very good, validates our *minimal* physical model.

The final paper will present additional results, notably on other erbium-doped fibers, other $L$, and EDLs at zero-dose rate. Physical differences with ytterbium-doped fibers will be explained. The model will be introduced in detail (physical bases, equations, determining parameters, limits…) and thoroughly confronted to data. Beyond the basic investigations performed here at high doses and high dose rates, practical predictions for low dose rates and low doses applications, including possible ELDRS, will be discussed.

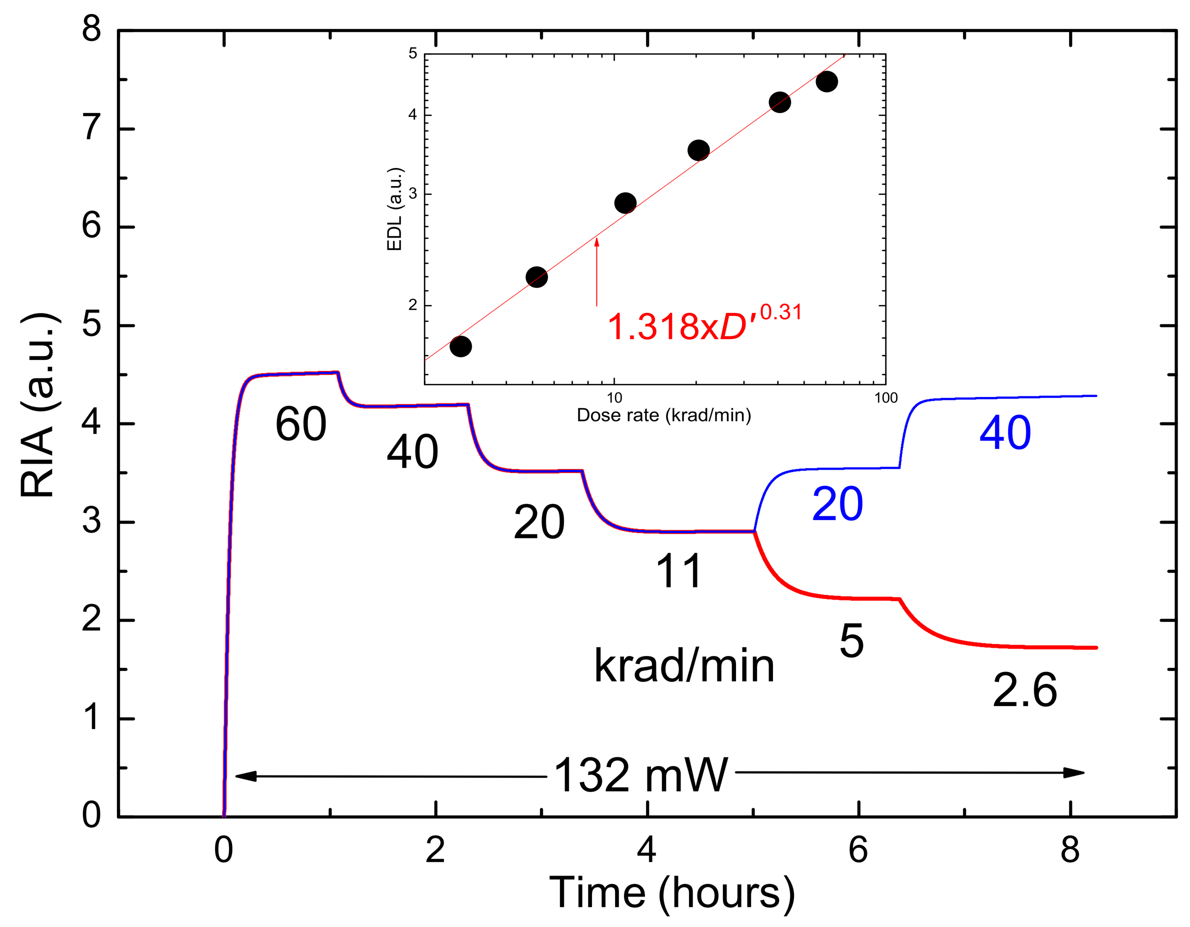


**Fig. 6.** Simulation of the first irradiation sequences of Fig. 2 (zone A) (red curve) and a variant (blue curve) showing that EDLs given by the model are well reproducible for identical ($P_{in}$, $D'$) couples. Inset: EDL as a function of the dose rate and its power law fit.

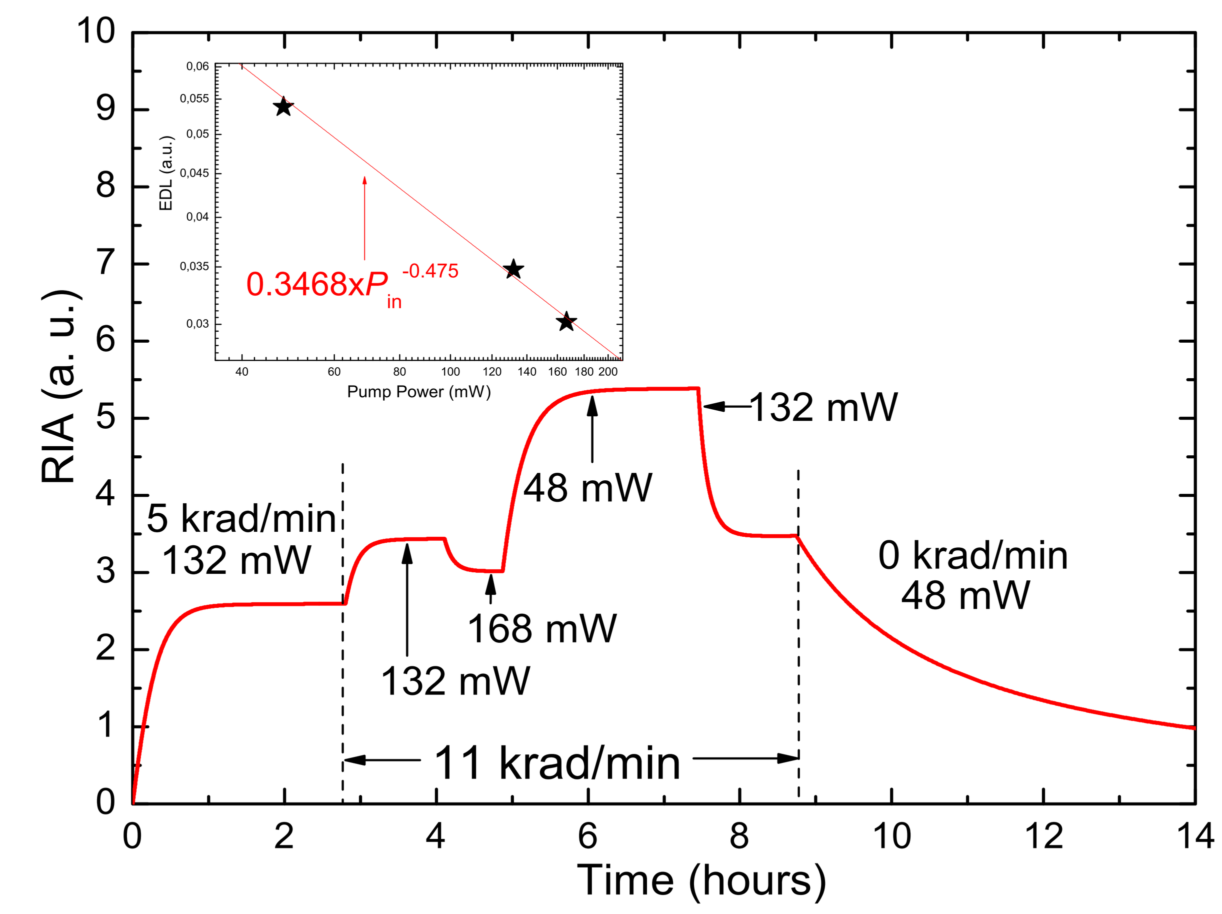


**Fig. 7.** Simulation of irradiation sequences of Fig. 2, zone B and beginning of zone C. Inset: EDL as a function of pump power and its power law fit.

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